PART 2 SEQUENCE STRATIGRAPHY AND SEA-LEVEL CHANGE

4 Sequence stratigraphy

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In this Chapter, we will examine the application of a revolutionary new concept that has now been widely applied to the sedimentary record. This concept, called sequence stratigraphy, has evolved over the past few decades and changed the way in which geologists interpret the development of sedimentary environments in time and space. Rather than being based either on correlation of rocks using lithology, fossils or other stratigraphical techniques (Section 2.1), or on facies analysis to construct past sedimentary environments and systems, sequence stratigraphy combines the two approaches and recognizes packages of strata each of which was deposited during a cycle of relative sea-level change and/or changing sediment supply. This genetic approach means that the packages of strata are bounded by *chronostratigraphical* surfaces (Box 2.1). These surfaces include unconformities formed during relative sea-level fall and flooding surfaces formed during relative sea-level rise.

Although the sequence stratigraphical technique was initially developed within the oil industry to help correlate rock units and hence predict new hydrocarbon reserves, sequence stratigraphy is now much more widely used for a number of reasons:

- To try to understand and predict gaps (unconformities) in the sedimentary record.
- To divide the sedimentary record into time-related genetic units, which are useful for stratigraphical correlation and prediction of facies.
- To obtain a holistic view of the distribution of sedimentary facies in time and space.
- To determine the amplitude and rates of past changes in sea-level, and so aid our understanding of the nature of crustal (e.g. fault movement, isostasy, ocean-floor spreading) and climatic processes operating in the past.
- To help identify, classify and understand the complex hierarchy of sedimentary cycles in the stratigraphical record. Sequence stratigraphy is useful for analysing cycles that range, in duration, from the 10 ka to >50 Ma scale.

Sequence stratigraphy is therefore a tool that allows geologists to draw together many different lines of evidence when analysing the fill of a sedimentary basin (Box 3.1). Geologists tend to use the logical thought progression of observation–process–environment to interpret sedimentary rocks. Using sequence stratigraphy, we will show how this thought progression can be taken one stage further to investigate sedimentary environments in both time and space. The predictive nature of the sequence stratigraphy model can greatly aid in integrating and correlating a range of depositional environments at a number of localities. In this way, a wider, more regional picture of the sedimentary deposits can be built up. By combining evidence from both the sedimentary packages and the unconformities, we can thus use sequence stratigraphy to gain a fuller picture of environmental changes documented in the sedimentary record through time.

4.1 Sediment accommodation space — principles and controls

Sequence stratigraphy emphasizes the importance of the space that is made available within a basin for sediment to be deposited and the amount of sediment supplied. In order for either marine or non-marine sediment to be deposited, there has to be space available to put it in; this is termed *accommodation space*. The amount of *marine* accommodation space is governed by changes in *relative* sea-level (Figure 4.1). In Sections 3.3 and 3.4, we discussed the fact that changes in relative sea-level are controlled by both eustatic sea-level fluctuations and tectonic subsidence/uplift (Figure 3.6). We also discussed the fact that eustasy and tectonic subsidence act independently of each other, so a eustatic sea-level fall coupled with a higher rate of tectonic subsidence will still result in a relative sea-level rise and hence an increase in accommodation space. For this reason, relative sea-level is used as an all-encompassing term for eustatic and tectonic changes and can be directly equated to changes in marine accommodation space. How tectonic movements and eustatic sea-level also control *non-marine* accommodation space is discussed later in this Section.

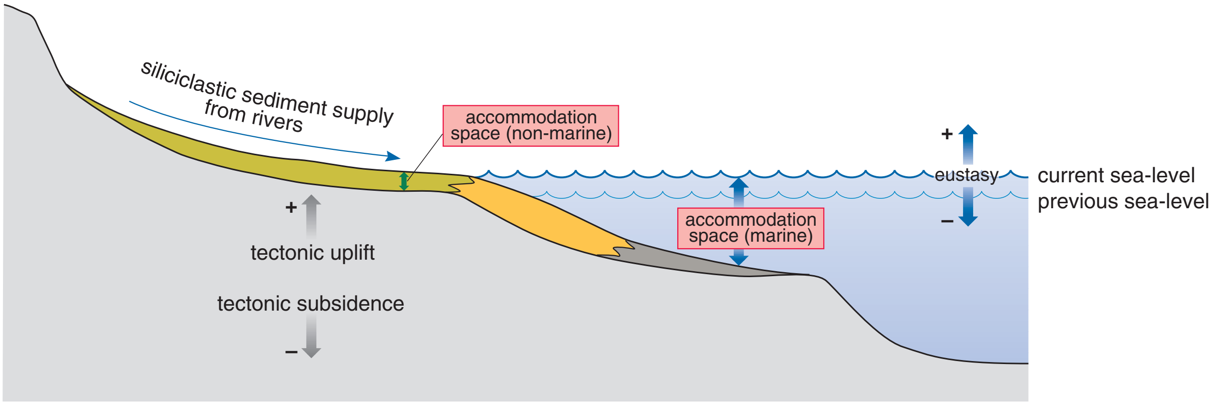


Figure 4.1 Sediment accommodation space and its relationship to eustatic sea-level and tectonic uplift and subsidence. Marine accommodation space created during a rise in relative sea-level has been partially filled with sediment (yellow and dark-grey), whereas the non-marine accommodation space created during the rise in relative sea-level has been totally filled with sediment (yellowish-green).

If there is zero accommodation space available, the sediments will be transported to an area of (positive) accommodation space where they can be deposited. Thus, areas of zero accommodation space are sites of sediment by-pass. If there is a negative amount of accommodation space, the previously deposited sediments will be eroded and transported to an area of (positive) accommodation space. This is because all sedimentary systems are trying to achieve and then preserve an *equilibrium profile* (or depositional profile) where the available accommodation space is balanced by the amount of sediment supplied.

○ What would happen if the sediment supply increased at a much greater rate than the increase in accommodation space?

● All the accommodation space would be filled with sediment, resulting in a regression and the deposition of a shallowing-upward succession.

Therefore, if either the *rate* of sediment supply or the *rate* of change of accommodation space is altered, the equilibrium will be upset. This will lead to regression (basinward or seaward shift of the shoreline) or transgression (landward shift of the shoreline) in marine areas and re-adjustment of the areas of deposition and erosion in land areas.

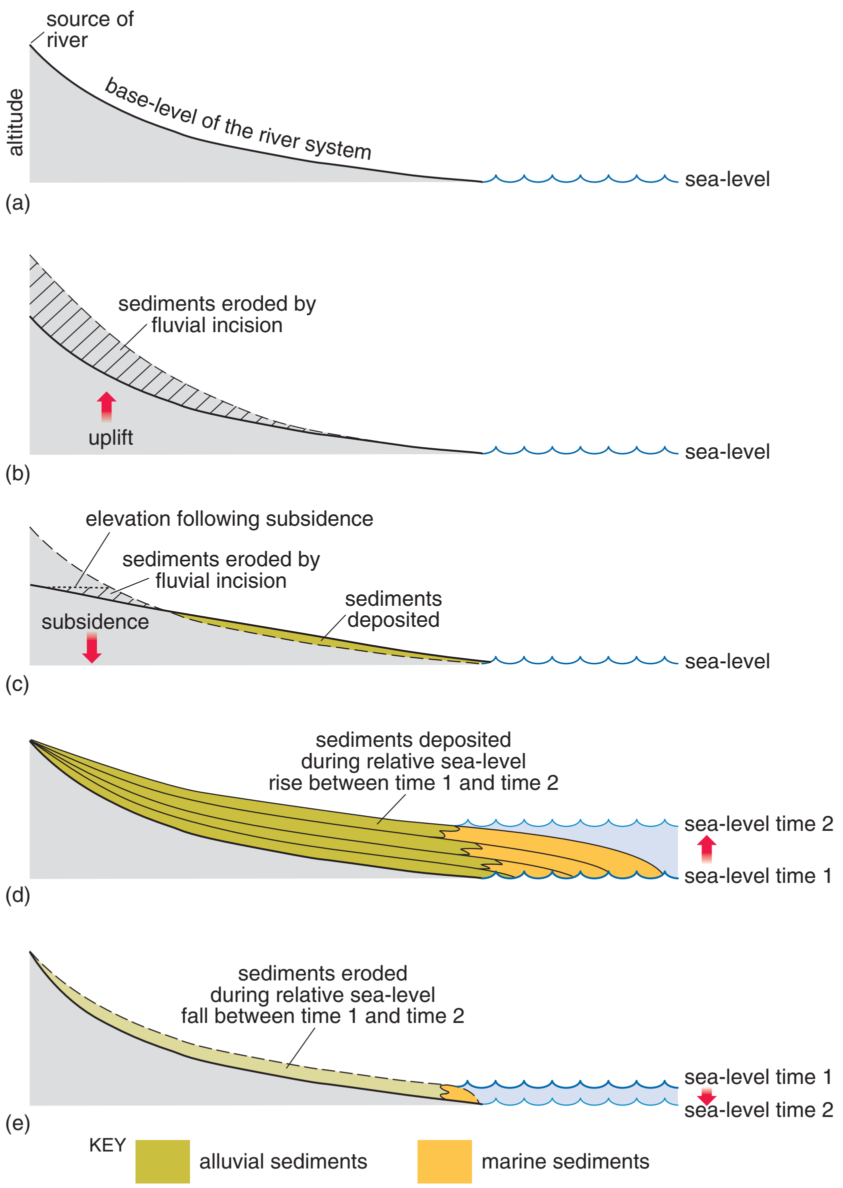


Figure 4.2 (a) The equilibrium profile of an alluvial system. In order to maintain the equilibrium profile, erosion or deposition of alluvial sediments will take place if there is a relative sea-level change and/or tectonic movement in the source area. (b) Erosion of sediments due to uplift of the source area. (c) Erosion and deposition of sediments along the alluvial profile due to subsidence of the source area. (d) Deposition of sediments due to a relative sea-level rise. (e) Erosion of sediments due to a relative sea-level fall.

The ideal equilibrium profile of an alluvial system (sometimes referred to as the longitudinal or depositional profile) is an exponentially curved topographical gradient from the source area to sea-level (Figure 4.2a); this curved topographical gradient is a result of the height of the source area and the increase in the rate of discharge downstream. Uplift of the source area will cause the rivers to cut down (or incise) and sediment to be removed (Figure 4.2b). Subsidence of the source area of the river will change the shape of the profile and the river system will re-adjust by eroding and depositing sediment to regain a stable equilibrium profile which will be flatter (Figure 4.2c). Similarly, a change in relative sea-level will also alter the equilibrium profile of the alluvial system. As relative sea-level rises, the position of the coastline with respect to the gradient of the equilibrium profile changes, the river channels infill and hence the gradient flattens out (Figure 4.2d). As relative sea-level falls, alluvial systems will cut a new lower river profile by incision (Figure 4.2e) until the alluvial system profile and sea-level are back in equilibrium. Rivers with an irregularly shaped equilibrium profile, for example due to individual fault movement, will erode and deposit sediment along the profile to establish an equilibrium. The level along the equilibrium profile below which sediment will be deposited and above which sediment will be eroded is referred to as *base level*.

In aeolian systems, the base-level is the water table, so deserts have a fairly flat equilibrium profile. Relative sea-level has a strong influence on the position of the water table, which is a key factor in the preservation of aeolian sediments.

○ How might the position of the water table in deserts affect the aeolian sediments preserved?

● Sediments that are situated below the water table stand a better chance of being preserved because: (i) they are wet and therefore not as easily transported by the wind; and (ii) they are preferentially cemented by minerals in the ground water. Therefore, the sediments situated above the water table are more likely to be eroded and transported.

In the shallow-marine setting, there is also an equilibrium profile governed by the position of high and low tide levels together with fairweather wave-base and storm wave-base (Figure 4.3), each of which defines the specific base-level for the individual coastal zones ranging from the backshore to offshore transition zone. However, when the whole equilibrium profile from the land to the deep sea is considered, these various base-levels are all relatively close to sea-level, so the latter can be effectively taken as base-level in marine environments. This is particularly true for carbonate environments where the greatest supply of carbonate grains and matrix is in shallow-marine areas and all the available accommodation space up to sea-level can be rapidly filled (Chapters 11 and 12). Other base-levels may be present along the continental shelf, for instance, where ocean currents regularly impinge on the sea-floor, but we shall not consider these in any detail here.

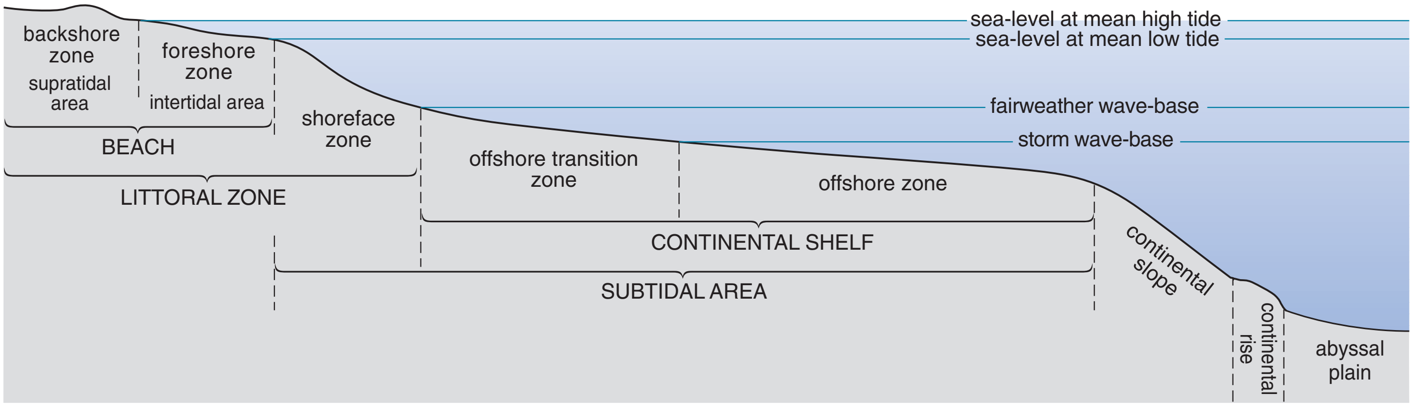


Figure 4.3 The shallow-marine equilibrium profile and various base levels discussed in the text; for simplicity, sea-level can be taken as the base-level in shallow-marine environments.

Equilibrium profiles in all environments ranging from alluvial to deep sea are perturbated by tectonic and climatic factors which also govern relative sea-level and sediment supply. Sea-level is thus particularly important in affecting deposition and erosion along both non-marine and marine equilibrium profiles. In the majority of circumstances, the amount of accommodation space above sea-level is generally less than it is below. Thus, in siliciclastic environments, sediment is transported from non-marine systems into the nearest accommodation space available, which is the shallow-marine setting. In carbonate environments, the majority of sediment is produced and accumulates in this shallow-marine setting. In the deep sea, below the edge of the continental shelf, there is a large amount of accommodation space but it is mainly underfilled as most of the sediment is deposited in the shallow-marine areas. We can think of shallow-marine environments as the 'sediment traffic jam' area (because it is the carbonate factory where the majority of carbonates are produced, and where the majority of siliciclastics are dumped by rivers). For this reason, the shallow-marine environment is the most sensitive area to changes in accommodation space and sediment supply.

The compaction of sediments over time is an additional mechanism by which there can be an increase in accommodation space. Compaction of sandstones may cause up to 30% reduction in sediment volume, whilst dewatering in mudstones may cause the sediment volume to decrease by up to 80% (compaction is discussed further in Section 5.3). Consequently, even if relative sea-level remains constant and sediment deposition ceases, it may still be possible for accommodation space to increase due to sediment compaction.

From this discussion, it should now be clear that changes in accommodation space and the rate at which it is filled are controlled by the interplay of a number of factors. Climate contributes to eustatic sea-level change through such mechanisms as glacio-eustasy, by controlling the rate of erosion and transportation of sediment from the higher inland areas (or hinterland) to the site of sediment deposition, and by controlling the rate at which carbonate sediment is generated. Tectonic movements determine the relative positions of the sea-bed and land surface and contribute to tectono-eustasy by altering the volume of ocean basins and hence the amount of accommodation space. Tectonic movements also affect sediment supply, and sediment compaction can increase accommodation space.

4.2 Filling basins with sediments and the development of parasequences

The simplest way to master sequence stratigraphy is to consider the ‘sediment traffic jam’ area of the coastal and shallow-marine siliciclastic depositional environments where changes in relative sea-level are easiest to interpret. Relative sea-level and therefore accommodation space, together with sediment supply vary over a number of different time-scales. A ‘bottom-up’ approach will be used, i.e. the smallest, simplest sequence stratigraphical depositional unit will be considered first. Then we will consider how these small-scale units stack together due to changes in accommodation space and/or sediment supply over longer time periods to form sequences.

The small-scale units are termed *parasequences*, and each of them results from a small-amplitude, short-term oscillation in the balance between sediment supply and accommodation space. To examine how each parasequence forms, we will consider a coastal environment where the rate of increase of accommodation space is less than the rate of sediment supply. As sediment enters the sea, it fills up the most proximal areas first, and then, because there is still more sediment than accommodation space, the sediment will be transported into more distal areas, causing the shoreline to move progressively basinward (or prograde, Figure 4.4a).

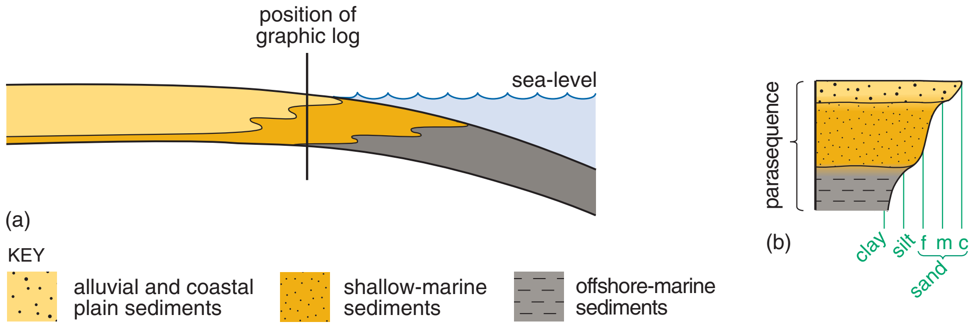


Figure 4.4 (a) Cross-section showing progradation of a coastal succession due to the rate of increase in accommodation space being less than the rate of sediment supply. (b) A simplified graphic log of the resultant coarsening-upward succession termed a parasequence.

In keeping with Walther's Law, the facies within this succession will represent conformable deposits that accumulated through time in progressively shallower-water depths, and thus any vertical succession through the parasequence is shallowing-upward and usually coarsening-upward, as higher, younger sediments are deposited under progressively more proximal, higher-energy conditions (Figure 4.4b). If the rate of sediment supply and rate of creation of accommodation space remained constant, the succession would continue to prograde into the basin until the sediment had filled all the available accommodation space.

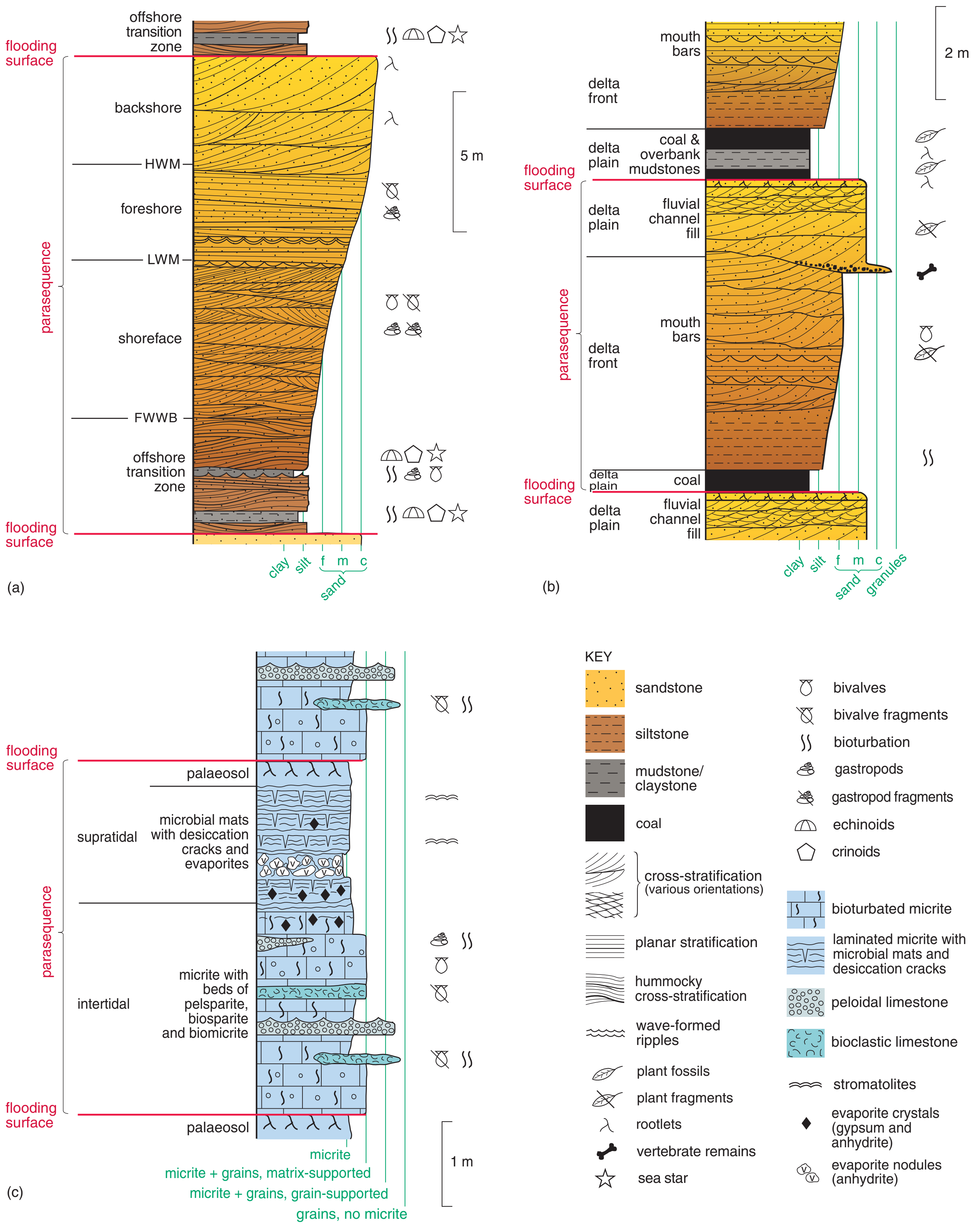
○ What will happen to the coastal shallowing-upward succession if there is an increase in the rate of creation of accommodation space (i.e. a relative sea-level rise) such that it is greater than the rate of sediment supply?

● The increase in accommodation space will cause transgression of the sea over the succession, terminating its shallowing-upward deposition.

The rock record shows that, in the majority of cases, this transgression event is marked either by a much thinner set of facies representing transgression or, more often, by a distinct surface which caps the succession, termed a *flooding surface* (there are a number of reasons why sediments representing small-scale short-term transgressions are not preserved, and these are described later in this Section). The flooding surfaces represent deepening and they cap each parasequence. Following transgression, a new parasequence will start to build out on top of the first one, utilizing the accommodation space that was newly created as relative sea-level rose.

A parasequence is thus a small-scale succession of relatively conformable beds or bed sets bounded by flooding surfaces. Parasequence thickness is highly variable, ranging from less than a metre to a few tens of metres. The lateral extent of parasequences varies between tens to thousands of square kilometres, depending on the geometry of the depositional area and the characteristics of the particular sedimentary system. They are the smallest bed-scale cycle (rather than laminar-scale) commonly observed in the sedimentary record and the smallest unit usually considered in sequence stratigraphical analysis. Figure 4.5 shows graphic logs of some typical parasequences. For instance, a strandplain succession of conformable beds representing the offshore transition zone, shoreface, foreshore and backshore might form a parasequence (Figure 4.5a), as would the coarsening-upward succession of delta front mouth bar sandstones overlain by the fluvial channel fills of the delta plain (Figure 4.5b) and a conformable succession of intertidal and supratidal carbonates (Figure 4.5c). Most parasequences coarsen upwards, as shallowing produces higher-energy conditions. A few parasequences fine upwards, e.g. in estuarine depositional settings or a muddy tidal flat to subtidal environment (Figure 4.5c); nevertheless these cycles still represent shallowing upwards.

Figure 4.5 (opposite) Parasequences from a range of sedimentary environments: (a) a siliciclastic strandplain succession; (b) a deltaic succession; (c) an intertidal to supratidal carbonate ramp succession.


offshore transition zone
flooding surface
backshore
HWM
foreshore
LWM
shoreface
FWWB
offshore transition zone
flooding surface
parasequence
5 m
clay
silt
f
m
c
sand
(a)
mouth bars
delta front
coal & overbank mudstones
delta plain
flooding surface
fluvial channel fill
delta plain
mouth bars
delta front
parasequence
delta plain
coal
flooding surface
delta plain
fluvial channel fill
2 m
clay
silt
f
m
c
sand
granules
(b)
flooding surface
palaeosol
supratidal
microbial mats with desiccation cracks and evaporites
parasequence
intertidal
micrite with beds of pelsparite, biosparite and biomicrite
flooding surface
palaeosol
micrite
micrite + grains, matrix-supported
micrite + grains, grain-supported
grains, no micrite
1 m
(c)
KEY
sandstone
siltstone
mudstone/ claystone
coal
cross-stratification (various orientations)
planar stratification
hummocky cross-stratification
wave-formed ripples
plant fossils
plant fragments
rootlets
vertebrate remains
sea star
bivalves
bivalve fragments
bioturbation
gastropods
gastropod fragments
echinoids
crinoids
bioturbated micrite
laminated micrite with microbial mats and desiccation cracks
peloidal limestone
bioclastic limestone
stromatolites
evaporite crystals (gypsum and anhydrite)
evaporite nodules (anhydrite)

Reasons why the deepening part of parasequences is not commonly preserved as transgressive sediments

There are several reasons why the deepening part of a parasequence is not represented by a succession of upward-deepening facies. These relate either to the mechanisms by which parasequences may form or the intrinsic conditions produced during deepening. During deepening in shallow-marine areas, wave processes will transport marine sediment landward, thus the sediment will be trapped in more proximal areas and not deposited until the following stillstand or shallowing. In addition, rivers that previously supplied sediment to the area will not incise and produce sediment because of flooding. Parasequences may also be asymmetric if the mechanism producing the accommodation space is subsidence on a fault. This may be an important mechanism in highly tectonically active areas but the movements need to be both repeated and pulsed. Many parasequences are deposited in subsiding areas so the rate of increase in accommodation space due to eustatic sea-level rise or compaction is greatly enhanced by the subsidence. In this case, the sedimentary system does not have a fast enough response time to keep up with rise so no sediments are deposited. Another asymmetric mechanism by which accommodation space is created is through compaction of sediments (Sections 4.1, 5.3). This is because compaction of the sediments can only result in deepening; the newly created accommodation space then progressively fills with sediment and a shallowing-upward succession is deposited.

4.2.1 Parasequence sets, progradation, aggradation and retrogradation

Now let us consider the patterns developed when a series of parasequences are superimposed on different longer-term trends in the delicate balance between sediment supply and accommodation space. Each parasequence and its overlying flooding surface represents one cycle of decreasing and increasing accommodation space for a steady sediment supply (Figure 4.4). But if we superimpose these short-term cycles on *longer-term* changes in the rate of sediment supply, or rate of change of accommodation space, it will lead to changes in the stacking pattern of the individual progradational parasequences and cause the next parasequence to start prograding from a different point. If the same longer-term trend continues over several parasequences, then successive parasequences will exhibit similar characteristics in their movement relative to the sediment source area. Successions of parasequences which form distinctive stacking patterns are termed *parasequence sets*. Progradational, retrogradational and aggradational parasequence sets are recognized. These different patterns are explained here with reference to a shallow-marine setting but the same patterns can be observed in other depositional settings.

Retrogradation

If for each *successive* marine parasequence the increase in accommodation space is *greater* than the constant rate of sediment supply, the deposits of each depositional zone in the successive parasequence will shift landward relative to those in the parasequence below it (Figure 4.6a). Because in this case the shoreline has moved in a landward direction, the parasequences are said to have *retrograded* (or backstepped) and a succession of parasequences showing this pattern is called a *retrogradational parasequence set* (Figure 4.7a). A retrogradational pattern would also result if for each successive parasequence the long-term rate of increase in accommodation space was constant but the rate of sediment supply decreased (Figure 4.7b).

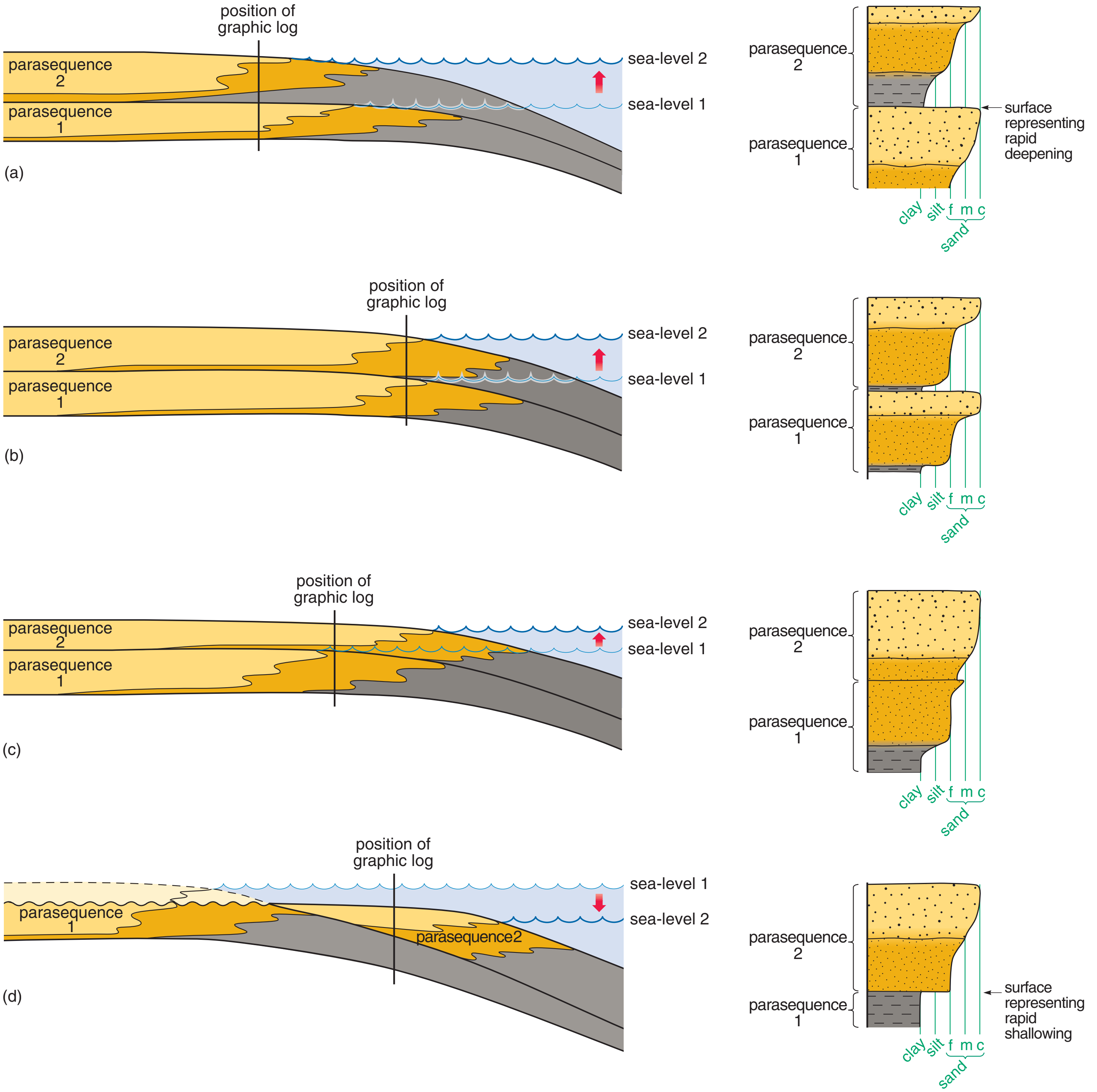


Figure 4.6 Cross-section and graphic logs showing the effects of long-term changes over two parasequences of: (a) an increase in the rate of creation of accommodation space (note that parasequence 2 is thicker than parasequence 1 on the left-hand side); (b) no change in the rate of creation of accommodation space; (c) a decrease in the rate of creation of accommodation space (parasequences 1 and 2 are the same thickness on the left-hand side); (d) a decrease in the amount of accommodation space (parasequence 2 is thicker than parasequence 1 on the left-hand side). Note that, if the accommodation space continues to decrease, it is unlikely that alluvial and coastal plain sediments will accumulate. The rate of sediment supply is assumed to be constant in each case.

Aggradation

If for each successive parasequence the increase in accommodation space is *equal* to the rate of sediment supply, the deposits of each depositional zone in the successive parasequence will build out from the same lateral position as the previous parasequence (Figure 4.6b). In this case, the shoreline will have stayed in the same position; the pattern is described as *aggradational* and a group of parasequences showing this pattern form an *aggradational parasequence set* (Figure 4.7c).

Progradation

If for each successive parasequence the increase in accommodation space is *less* than the constant rate of sediment supply, the deposits of each depositional zone in successive parasequences will shift basinward relative to those in the parasequence below (Figure 4.6c). Because in this case the shoreline has moved in a basinward direction, the parasequences are described to have *prograded* and a succession of parasequences showing this pattern is called a *progradational parasequence set* (Figure 4.7d). Progradation would also result if for each successive parasequence the long-term rate of increase in accommodation space was constant but the rate of sediment supply increased (Figure 4.7e). Depending on exactly how much the rate of increase in accommodation space is less than rate of sediment supply, a spectrum of different types of progradational geometry will result (Figure 4.7d–g). However, because in *every* case the shoreline and facies belts move in a basinward direction, they are all classified as progradational. If there is a decrease in accommodation space between parasequences 1 and 2, but sediment is still being supplied, the more proximal areas will be exposed above sea-level and will therefore be subject to subaerial erosion (Figure 4.6d). Accommodation space will be reduced in all areas, forcing the shoreline to shift rapidly basinward, to a position from which the new marine parasequence will start prograding.

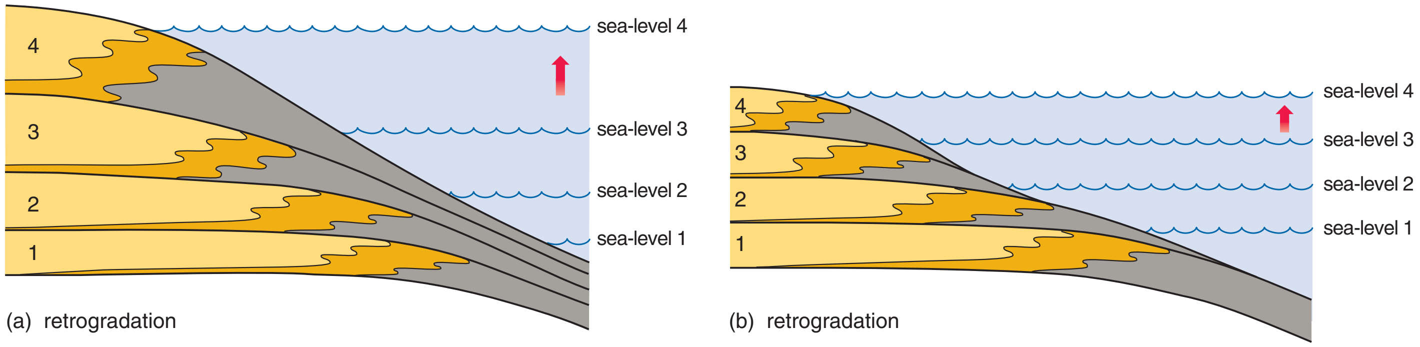
○ What are the relative contributions of accommodation space and sediment supply to the progradational geometry in Figure 4.7e compared to Figure 4.7g?

● In Figure 4.7e, the rate of sediment supply is greater than the rate of increase in accommodation space in order for the parasequence set to prograde and for each parasequence to have the same thickness in the proximal area and a greater thickness in the distal area. However, in Figure 4.7g, there is a decrease in the amount of accommodation space because of a relative sea-level fall. This is independent of the amount of sediment supply.

In fact, Figure 4.7g is the only one to show a relative sea-level fall (a decrease in accommodation space). This leads us on to an important concept, which is the distinction between two types of regression, as explained in Section 4.2.2.

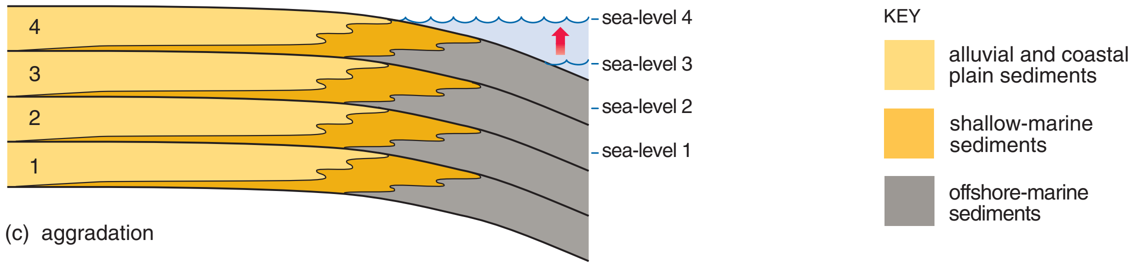
4.2.2 Regression and forced regression

In sequence stratigraphy, a distinction is made between '*regression*' and '*forced regression*'. Whilst these are both processes that involve a decrease in accommodation space compared to the rate of sediment supply, they result from different mechanisms. A 'normal' regression (i.e. basinward migration of the shoreline) occurs when the rate of *increase* in accommodation space (through either a relative sea-level rise (Figure 4.7d,e) or a stillstand (Figure 4.7f)) is less than the rate of sediment supply. In this case, all the available accommodation space is filled with sediment and a regressive succession is deposited. Periodic regression and

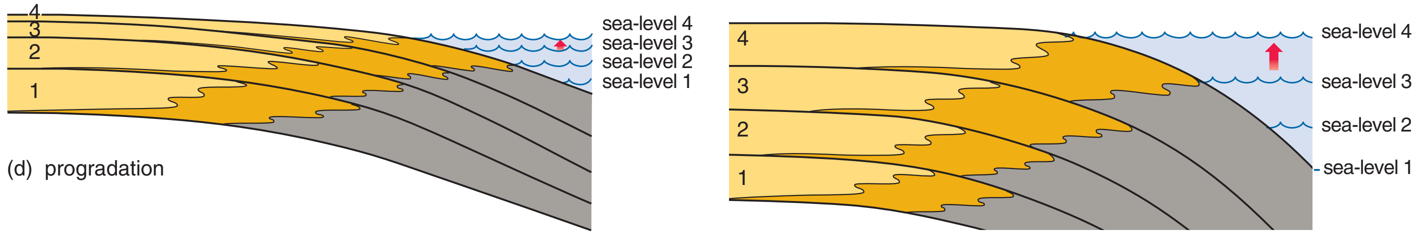


(a) retrogradation

(b) retrogradation

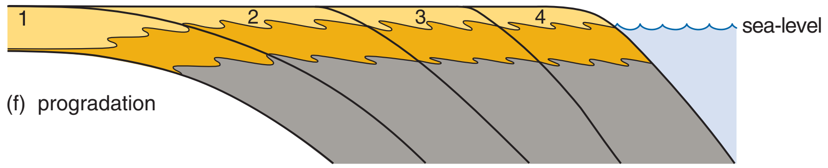


(c) aggradation

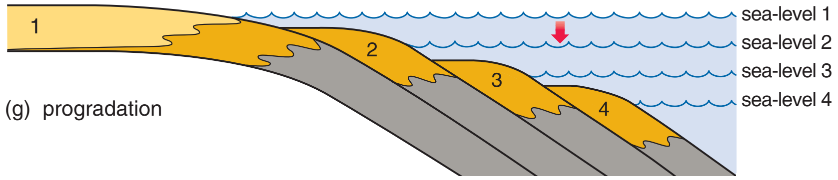


(d) progradation

(e) progradation



(f) progradation



(g) progradation

Figure 4.7 Stacking patterns of parasequences. (a) Retrogradational parasequence set resulting from an increase in the rate of creation of accommodation space for each parasequence that is greater than the constant sediment supply (as shown by the increase in distance between each sea-level). (b) An alternative retrogradational parasequence set resulting from a constant rate of increase in accommodation space (as shown by the equal distance between each rise in sea-level) between parasequences but a decrease in the rate of sediment supply. (c) Aggradational parasequence set resulting from the rate of sediment supply being matched by the rate of increase in accommodation space. (d) Progradational parasequence set resulting from the rate of creation of accommodation space between parasequences being less than the constant rate of sediment supply. (e)–(g) Alternative progradational parasequence sets. (e) Progradational parasequences resulting from a constant rate of increase in accommodation space and an increase in the rate of sediment supply. For (f), there is no long-term increase in accommodation space (i.e. a sea-level stillstand) but there is a continuous sediment supply. See text for explanation of (g).

transgression may occur, for instance, in a basin with a fairly constant subsidence but fluctuating sediment supply. In contrast, a forced regression is a specific case in which the accommodation space is *decreased* by a relative sea-level fall (which in turn could be due to either the rate of eustatic sea-level fall exceeding the rate of tectonic subsidence or the rate of eustatic sea-level rise being less than the rate of tectonic uplift). Forced regressions are independent of the variations in sediment supply. In every case of forced regression, the shoreline will not only be moved basinward but will also be moved *lower* down the depositional profile than it was previously.

❍ Which part(s) of Figure 4.7 results from a forced regression? Give a reason for your answer.

● Figure 4.7g results from a forced regression because this is the only example where the shoreline is lower than it was previously.

Sediment supply, particularly for siliciclastic environments, can be significant during a forced regression, because regardless of any rivers that were already transporting sediment into the basin, additional sediment will be derived by subaerial erosion and fluvial incision into the previously deposited sediments as relative sea-level falls.

Now that we have seen the way in which changes in accommodation space caused by changes in relative sea-level, and changes in sediment supply, control the internal stacking geometries of parasequence sets on the short time-scale, we will step up our scale of observation to investigate how the same controls operate over longer time-scales and at greater amplitudes to control the stacking of successive parasequence sets.

4.3 Sequences and systems tracts

A *sequence* or *depositional sequence* is composed of a succession of parasequence sets. Parasequences are the building blocks of sequences. Each sequence represents one cycle of change in the balance between accommodation space and sediment. Some sequences are characterized by forced regressions whereas others show only regression. Sequences generally range in thickness from a few metres to tens or even hundreds of metres in thickness, and they are the next larger (and longer-duration) cycles above parasequences. Similar to parasequences, sequences are the result of either changes in eustatic sea-level, or subsidence/uplift, or changes in sediment supply, or a combination of any of these factors. Every sequence is composed of *up to* four '*systems tracts*' each of which represents a specific part in the cyclic change in the balance between accommodation space and sediment supply. Each systems tract is made up of at least one parasequence set. Different conditions may result in one or more of the systems tracts not being developed and/or preserved. This is quite common in the geological record. The concepts presented in Sections 4.2 and 4.3 are used to identify and discuss the evidence for relative sea-level change in the sedimentary record.

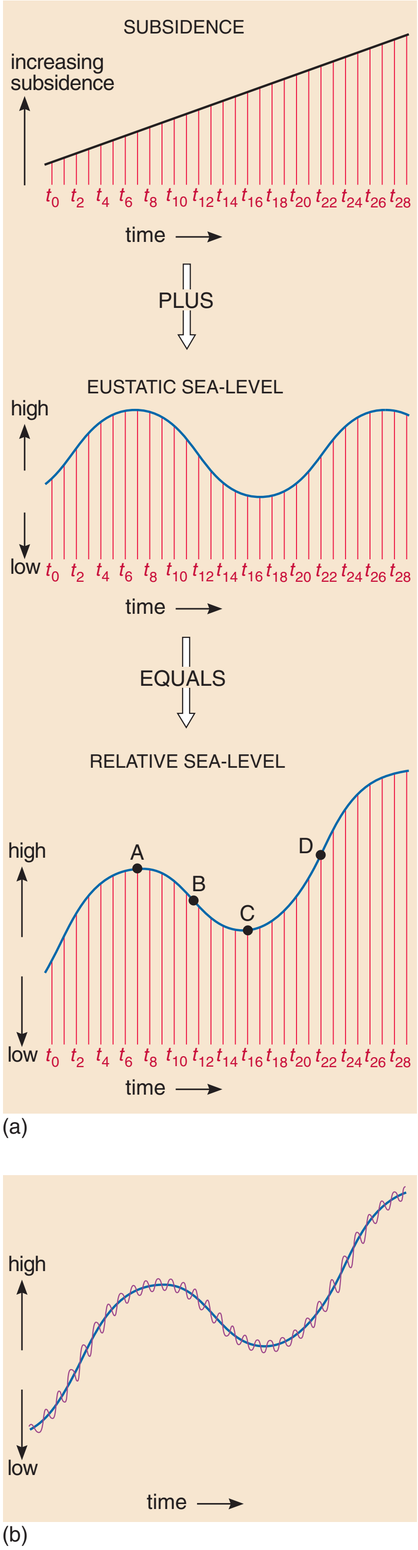


Figure 4.8 Sea-level curves used in Section 4.3: (a) relative sea-level curve derived from addition of a uniform subsidence rate and a sinusoidal change in eustatic sea-level; (b) complex curve (shown in purple) that results from combining the relative sea-level curve in (a) with shorter-term changes in accommodation space associated with the development of parasequences. Equal time divisions are shown by red lines numbered t_0, t_1, etc. In the example described in this Section, each of these time units is assumed to be the time taken for the deposition of a parasequence. A–D are described in the text, which provides further explanation.

4.3.1 The construction of a sequence

The high number of different factors, such as subsidence rate, sediment supply, eustatic sea-level change, climate and lithology type involved in any one geological situation means that the resultant sequences are *highly* variable. However, every sequence has similar genetic components related to changes in the rate of accommodation space creation and sediment supply. We will explore the effect of such changes by considering the idealized stratigraphy resulting from one cycle of relative sea-level change produced by superimposing a sinusoidal change in eustatic sea-level on a uniform rate of subsidence; this is illustrated in Figure 4.8a.

○ Using Figure 4.8a, decide whether or not there will be any forced regressions, and give a reason for your answer.

● Yes, there will be a forced regression between time 7 (t_7) and time 16 (t_{16}) because the rate of eustatic sea-level fall shown is greater than the rate of subsidence (note that the lower part of Figure 4.8a shows a decrease in relative sea-level between point t_7 and t_{16}. This will result in relative sea-level fall, which will cause a forced regression.

For simplification, the changes in accommodation space associated with each parasequence are not shown on the sea-level curves included in later Figures in this Section. In this case, the duration is assumed to be the same for each parasequence. Figure 4.8b shows what the curve would look like if the short-term parasequence-related changes were added. Also for simplification, the rate of sediment supply will be assumed to be constant so that each parasequence contains the same volume of sediment. We will examine two depositional profiles from the land to the sea: (i) a shelf-break margin; that is, a margin with a narrow continental shelf and pronounced change in gradient at the shelf break (Figure 4.9a); and (ii) a ramp which dips at a shallow angle away from the alluvial profile to the deep sea (Figure 4.9b). There are up to seven genetic features formed in the sedimentary record during one sequence cycle which are described in stages in the text and Figures below.

Absolute sea-level and rates of sea-level change

We need to consider both absolute highs and lows in relative sea-level together with *rates* of relative sea-level change. It is important to distinguish between absolute highs and lows of relative sea-level and *rates* of relative sea-level change, because as demonstrated in Sections 4.1 and 4.2 it is the *rate* of change that governs how much new accommodation space is being created (or destroyed) at any one time. To explore these issues, consider the following two questions.

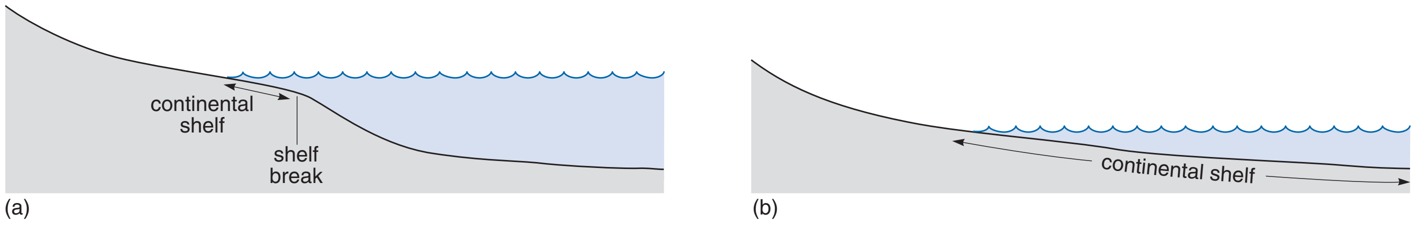


Figure 4.9 Depositional profiles considered in this Section: (a) a shelf-break margin; (b) a ramp which dips at a shallow angle.

- ❍ Where on the sea-level curve in Figure 4.8a is relative sea-level (a) rising at its maximum rate and (b) falling at its maximum rate?

- ● (a) Although relative sea-level is rising between the trough and the following peak on the sea-level curve, the maximum *rate* of rise is at the mid-point between the two, i.e. at the inflection point (D on Figure 4.8a). It is therefore at this point in time that accommodation space is being created most rapidly. (b) It therefore follows that the maximum *rate* of fall is located at the mid-point between the highest and subsequent lowest relative sea-level (i.e. between the peak and the next trough; marked B on Figure 4.8a).

- ❍ At which points on the sea-level curve is the rate of relative sea-level change zero?

- ● At the peaks and troughs (i.e. the maximum and minimum, marked A and C on Figure 4.8a) of the curve when relative sea-level is at its highest or lowest respectively. It is here that new accommodation space is being neither created nor destroyed.

The highstand systems tract (HST)

Consider Figure 4.10: part (b) shows that between t_0 and t_7, relative sea-level is rising so new accommodation space is being created. Between t_0 and t_2 for the relative sea-level curve chosen, the amount of new accommodation space created is the same for each of these two parasequences and is balanced exactly by the sediment supply. So, the parasequences deposited from t_0 to t_1 and t_1 to t_2 will be stacked aggradationally (note that each individual parasequence will still be progradational). Now consider t_2 to t_3: relative sea-level is still rising but at a lower rate than between t_0 and t_2, thus the amount of new accommodation space being created in the proximal areas is less than the amount of sediment being supplied for this parasequence (remember that each parasequence contains the same volume of sediment). Consequently, the sediments deposited between t_2 and t_3 are transported further into the basin where there is available accommodation space and thus the parasequence progrades relative to the two parasequences below. As relative sea-level approaches its maximum as shown by the curve, the *rate* of relative sea-level rise continues to decrease and thus each parasequence progrades further into the basin (Figure 4.10b). At t_7, the rate of relative sea-level rise is zero, and no new accommodation space is created.

This package of sediment deposited between the maximum rate of relative sea-level rise and maximum relative sea-level is termed the *highstand systems tract*, or HST for short. The HST is composed of aggradational to progradational parasequence sets (Figure 4.10c,d). Depending on the conditions, the base of the HST may form later than the maximum rate of relative sea-level rise (see later discussion in this Section).

The sequence boundary (SB)

Just after t_7 (Figures 4.10, 4.11 overleaf), relative sea-level starts to fall; this will result in the sea-level being lower than the top of the coastal sediments deposited at t_7 and the equilibrium profile re-equilibrating by eroding into the previously deposited alluvial and coastal facies. Sediment from incised river valleys will be transported out into the sea, where accommodation space is available. Thus, in the alluvial, coastal plain and nearshore areas, no sediment will be deposited and the proximal part of the depositional profile will become an area of sediment by-pass and an unconformity surface will start to form. As relative sea-level continues to

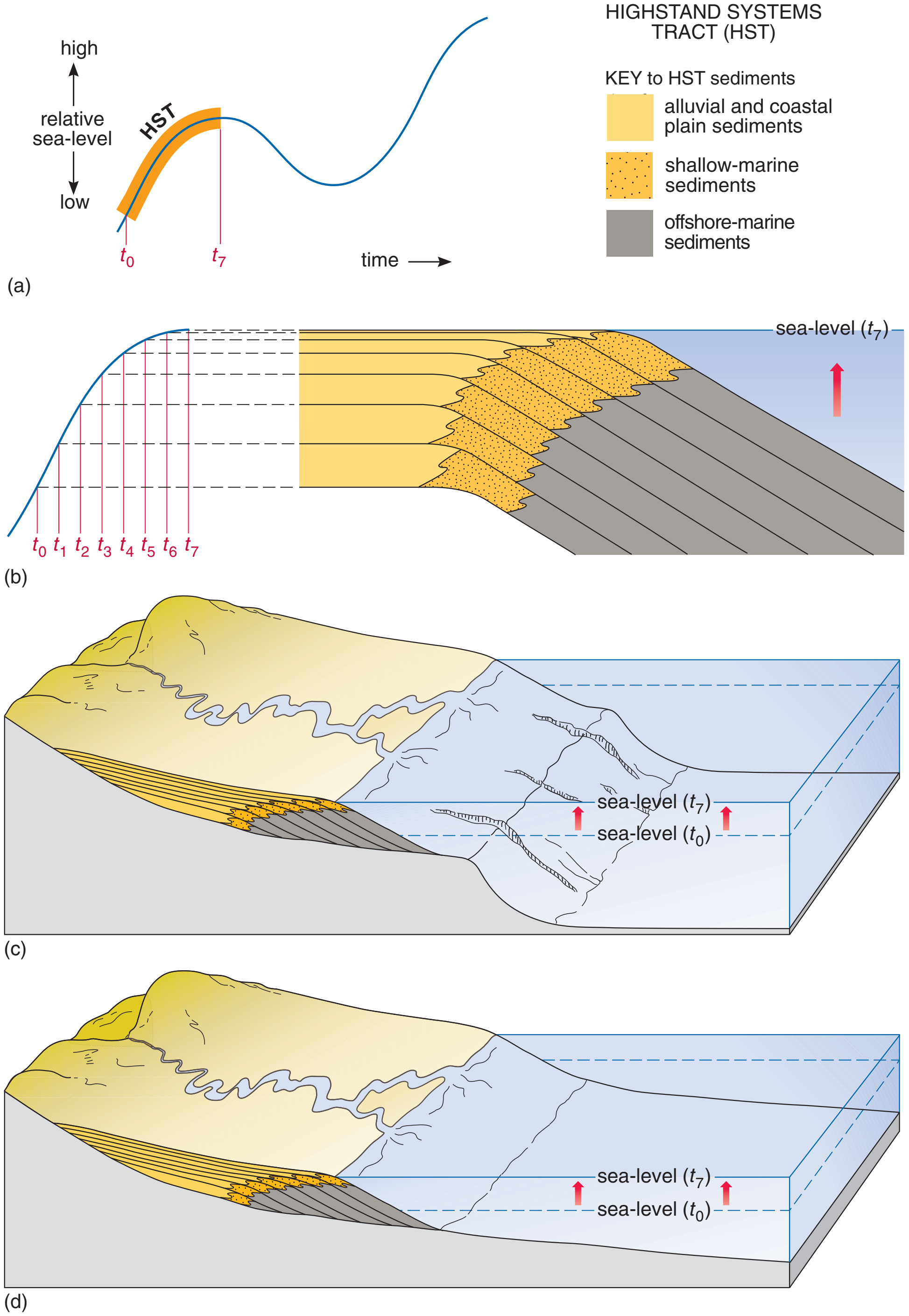
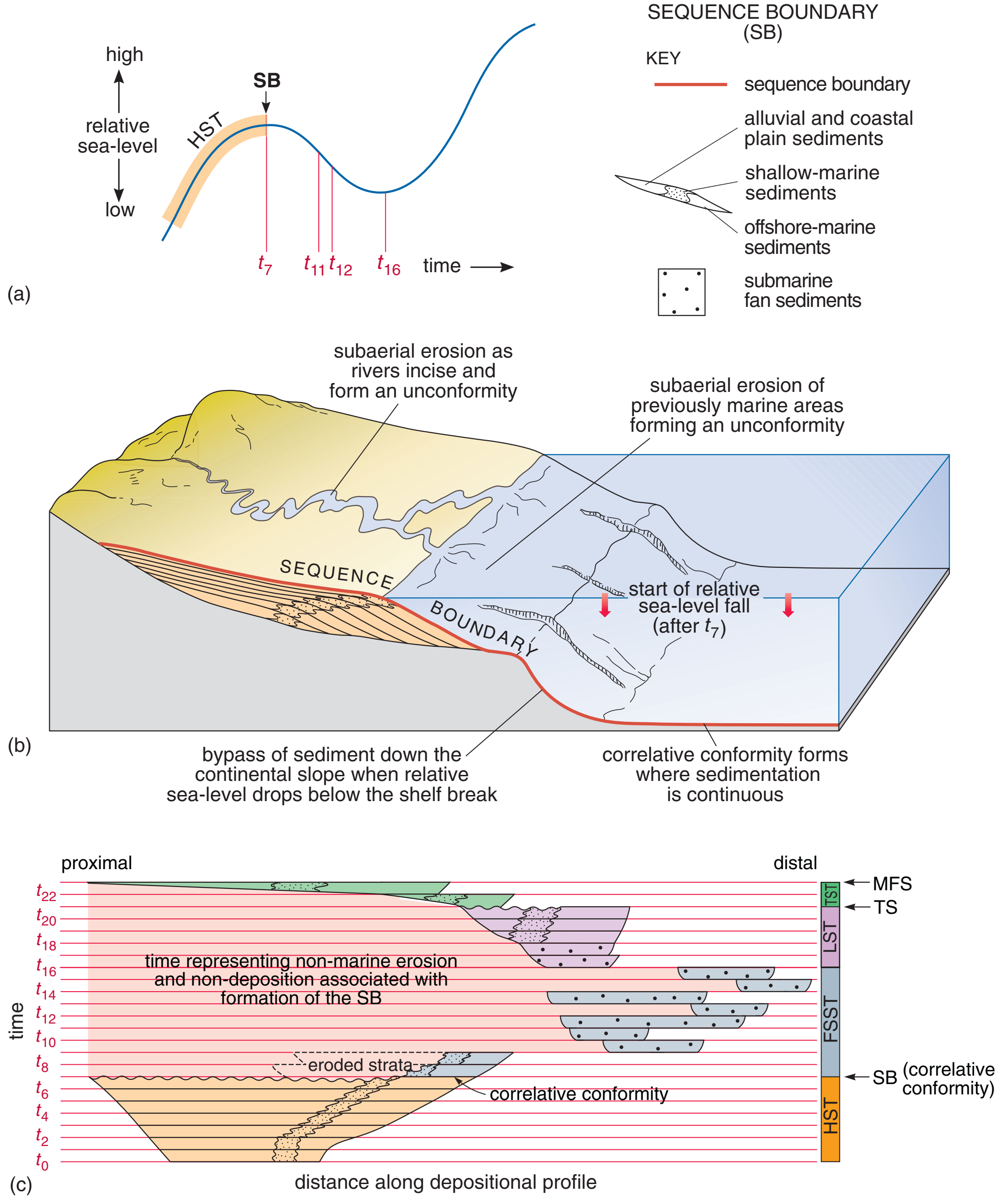


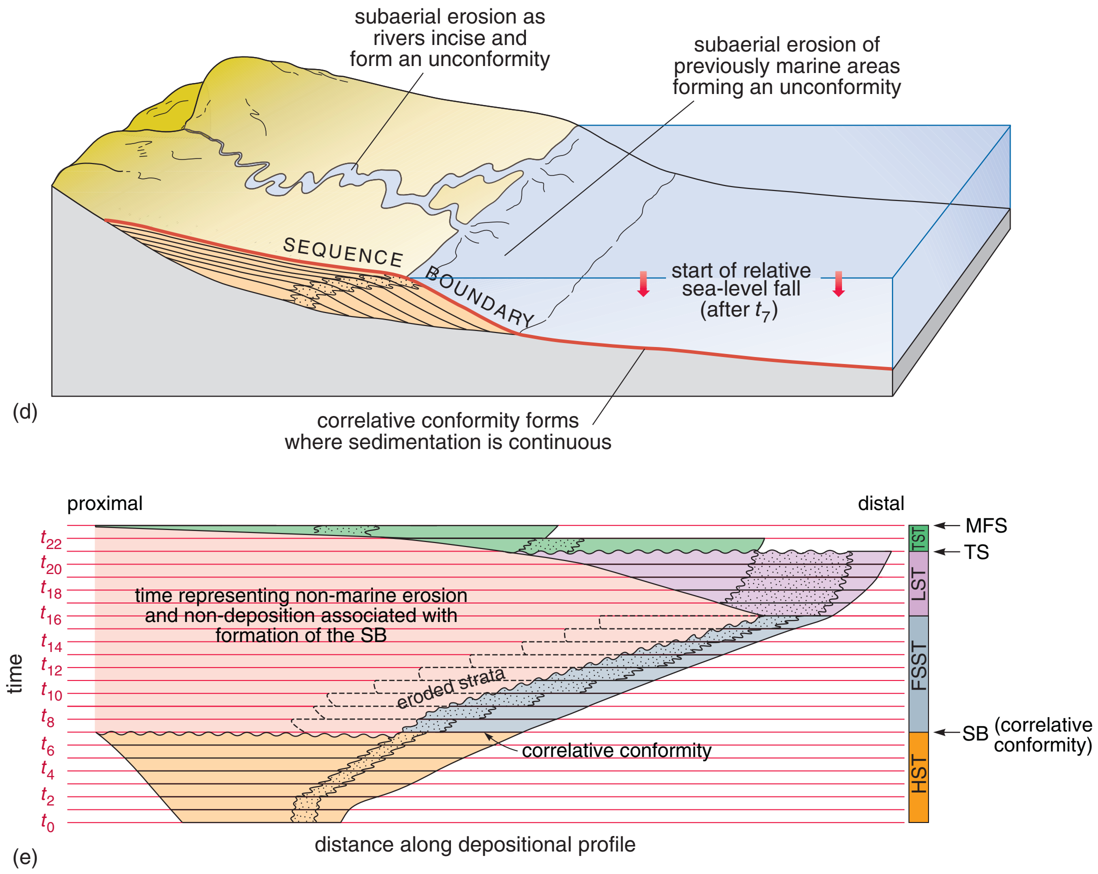
Figure 4.10 Features of the highstand systems tract (HST). (a) Interval on the theoretical relative sea-level curve shown in Figure 4.8, during which the HST is deposited. (b) Detail of the relative sea-level curve (in blue) and the HST sediments deposited. The curve spans a phase of decreasing relative sea-level rise (i.e. a decrease in rate of creation of accommodation space). The relative sea-level curve is divided into equal time units (red lines t_1, t_2 etc.). Dashed horizontal black lines in the middle indicate the amount of accommodation space created during each time step in the relative sea-level rise. The right-hand part shows the sediments deposited for each of the equal time intervals, assuming a constant rate of sediment supply. Note how the decrease in accommodation space in the proximal areas results in an aggradational to progradational parasequence stacking pattern. Sediments deposited over the time interval between the maximum rate of sea-level rise and maximum sea-level form the HST. (c) Typical geometry and features of the HST along a margin with a shelf break. Note that in the example illustrated, the HST did not prograde as far as the shelf break. (d) Typical geometry and features of the highstand systems along a ramp margin. (c) and (d) not to scale.

Figure 4.11 Features of the sequence boundary (SB). (a) Interval (t_7–t_{16}) on the theoretical relative sea-level curve where the sequence boundary forms. t_7 = initiation of sequence boundary formation and time of formation of the correlative conformity. t_{16} = last point where fluvial incision can take place. (b) Geometry and features of the sequence boundary along a margin with a shelf break. (b) and (d) Sediments that may be deposited simultaneously with formation of the sequence boundary are not shown. (c) Chronostratigraphical diagram from t_0–t_{22} to show the time represented by the unconformity surface of the sequence boundary (shaded in pink) and its relationship in time to the correlative conformity surface. (d) Geometry and features of the sequence boundary along a ramp margin. (e) Chronostratigraphical diagram from t_0–t_{22} showing similar features to (c). Note that for simplicity the hemipelagic and pelagic sediments that will be deposited in the deeper part of the basin are not shown; the correlative conformity will pass through these. Deposits shown above the correlative conformity part of the sequence boundary (t_7) in (c) and (e) are discussed later in this Section. (b) and (d) are not to scale.



fall, the rivers will continue to incise, and further sediment will be eroded. These three processes of incision, sediment by-pass and forcing of sediments further and further into the basin will reach their greatest at the maximum rate of relative sea-level fall (between t_{11} and t_{12}, Figure 4.11a). The three processes, at progressively reducing rates, will continue until the lowest point in relative sea-level is reached at t_{16}. As relative sea-level starts to rise again, sediment by-pass will continue until the by-pass area is flooded by the relative sea-level rise, but the downstepping of the shoreline and incision will cease. What happens to the sediments transported out into the sea during falling relative sea-level is discussed overleaf (the falling stage systems tract (FSST)).

In summary, the potential results of this relative sea-level fall will be incised river valleys, subaerial erosion and exposure of previously deposited marine sediments, marine erosion of sediments as currents and wave-base impinge lower down on the sea-floor, and transport and deposition of the eroded sediment to progressively more basinward positions. In carbonate environments, relative sea-level fall may cause



the sediments to dissolve away rather than be redeposited; this is discussed further in Chapter 12. The surface representing this relative sea-level fall, formed during sediment by-pass and erosion, and which will underlie any sediments deposited during the falling relative sea-level, is an unconformity and is termed the *sequence boundary*. The amount of time represented by the sequence boundary will vary along the depositional profile. It will represent the greatest amount of time in the proximal areas where by-passing and erosion occurred earlier, and where the sedimentary deposits that overlie the unconformity were deposited later when the shoreline reached its most proximal location as relative sea-level rose again (see text later in this Section). This chronostratigraphical relationship is illustrated in Figure 4.11c and e. In this representation, the horizontal axis represents distance along the proximal to distal profile and is exactly the same as Figure 4.11b and d respectively. However, the vertical axis represents time instead of thickness. Thus, these chronostratigraphical diagrams * illustrate where and during which time intervals sediment was deposited and preserved and where it was never deposited or was later removed by erosion. This type of diagram is widely used to show the time represented by unconformities or periods of non-deposition and their lateral extent.

○ As the sequence boundary is traced further offshore into the more distal sections, or into an area of higher subsidence, explain if you would still expect it to be marked by an unconformity.

● No, it will not be marked by an unconformity in these areas because this is where most of the sediment will have been transported to. Although accommodation space was also reduced here, it was never zero or negative, so deposition continued unabated during the relative sea-level fall.

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* Chronostratigraphical diagrams are also sometimes referred to as Wheeler diagrams, after H. E. Wheeler who wrote a famous scientific paper on them that was published in 1958.